The Transition to Axisymmetrical Mass Loss

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Abstract

Any model for the formation of elliptical planetary nebulae (PNs) should account for the positive correlation between the mass loss rate and the degree of departure from sphericity of the AGB progenitor's wind. I propose that this correlation results from dust formation above magnetic cool spots. The model deals with elliptical PNs, but not with bipolar PNs. The basic assumption is that a weak dynamo amplifies magnetic fields in AGB stars, such that magnetic cool spots are formed, mainly near the equatorial plane. Enhanced dust formation above these cool spots leads to a higher mass loss rate in the equatorial plane, resulting in the formation of an elliptical PN. The dust formation above cool spots becomes much more efficient when mass loss rate is high. In addition to explaining the correlation, the model has the advantage that it can operate for very slowly rotating AGB stars, having rotation velocities of less than 10^{-4} times the break-up velocity. Such velocities can be achieved by a planet companion of mass $\sim 0.1 M_{\text{Jupiter}}$ which spins-up the envelope, or even from singly evolved stars which leave the main sequence with a high rotation velocity. The sporadic nature of magnetic cool spots also leads to the formation of filaments, arcs, and clumps in the descendant PN. The model cannot explain the presence of jets and ansae in elliptical PNs. These are attributed to the destruction of a planet or brown dwarf on the AGB core.

1. Introduction

The inner regions of many planetary nebulae (PNs) and proto-PNs show much larger deviation from sphericity than the outer regions (for catalogs of PNs and further references see, e.g., Acker *et al.* 1992; Schwarz, Corradi, & Melnick 1992; Manchado *et al.* 1996; Sahai & Trauger 1998; Hua, Dopita, & Martinis 1998). By "inner regions" we refer here to the shell that was formed from the superwind−the intense mass loss episode at the termination of the AGB, and not to the *rim* that was formed by the interaction with the fast wind blown by the central star during the PN phase (Frank, Balick, & Riley 1990). This type of structure suggests that there exists a correlation, albeit not perfect, between the onset of the superwind and the onset of a more asymmetrical wind. In extreme cases the inner region is elliptical while the outer region (outer shell or halo) is spherical (e.g., NGC 6826, Balick 1987). Another indication of this correlation comes from spherical PNs. Of the 18 spherical PNs listed by Soker (1997, table 2), $\sim 75\%$ do not have superwind but just an extended spherical halo.

I consider two types of mechanisms that can in principle cause this correlation. In the first type (§2) a primary process or event causes both the increase in the mass loss rate and its deviation from spherical geometry. A primary mechanism or event may be external or internal to the star. An external event is a late interaction with a stellar or substellar companion (Soker 1995; 1997), while an internal mechanism can be the rapid changes in some of the envelope properties on the upper AGB due to a high mass loss rate and the rapid decrease of the extended envelope mass. Such changes can lead to mode-switch to nonradial oscillations (Soker & Harpaz 1992), or an increase in magnetic activity when the density profile below the photosphere becomes much shallower, and the entropy profile much steeper (Soker & Harpaz 1999). In the second type (§3), the increase in the mass loss rate on the upper AGB (the so called superwind) makes possible a mechanism which is very inefficient at low mass loss rates (Soker 2000).

In the present paper I review four recent works on this topic, all deal with enhanced dust formation, hence enhanced mass loss rate, above magnetic cool spots on the surface of AGB stars (Soker 1998; Soker & Clayton 1999; Soker& Harpaz 1999; Soker 2000). The mechanisms proposed here do not invoke any new mass loss mechanism, but use the generally accepted model for the high mass loss rate on the upper AGB, which includes strong stellar pulsations coupled with large quantities of dust formation at a few stellar radii around the stellar surface (e.g., Wood 1979; Jura 1986; Knapp 1986; Bedijn 1988; Bowen & Willson 1991; Fleischer, Gauger, & Sedlmayr 1992; Woitke, Goeres, & Sedlmayr 1996; Habing 1996; Höfner & Dorfi 1997; Andersen, Loidl, & Höfner 1999). Again, the proposed mechanism(s) applies (apply) only to elliptical PNs, and not to bipolar PNs. The latter require stellar companions.

2. Magnetic Cool Spots

In the first paper (Soker 1998), I presented the basic ingredient of the model. The main assumption is that dynamo magnetic activity results in the formation of cool spots, above which dust forms much easily. The dynamo dictates a general stronger activity toward the equator, but with significant sporadic behavior. The sporadic behavior leads to the formation of filaments, arcs, and clumps in the descendant PN. The enhanced magnetic activity toward the equator results in a higher dust formation rate there, hence higher mass loss rate. In that paper I assumed that the dynamo activity increases as the star ascends the AGB. Independently, mass loss rate increases as well, due to the increase of the density scale height (Bedijn 1988; Bowen & Willson 1991). In this model, the increase of dynamo magnetic activity is attributed to the decreasing density of the envelope, due to mass loss and expansion, which makes the density profile below the photosphere much shallower and the entropy profile much steeper (Soker & Harpaz 1999). The main points of the analysis of Soker (1998) and Soker & Harpaz (1999) are as follows.

(1) In order for the dynamo to stay effective to the upper AGB, the AGB star should be spun-up by a companion, and/or the dynamo must be effective even for rotation velocity of $\omega \sim 10^{-5}\omega_{\mathrm{Kep}}$, where ω_{Kep} is the Kepler velocity of a test particle on the equator. For the envelope spin-up, if it occurs on the upper AGB, a planet companion of mass $\sim 0.1 M_{\mathrm{Jupiter}}$ is sufficient. Born-again AGB stars may hint that the mechanism is efficient even for $\omega \sim 0.3 \times 10^{-4}\omega_{\mathrm{Kep}}$.

2) The angular velocity decreases rapidly as the envelope mass decreases toward the termination of the AGB. In the model this decrease is more than compensated by the increase of the vulnerability of dust formation and photospheric conditions to the magnetic activity, due to the shallower density profile and steeper entropy profile.

3) The required magnetic activity $\dot{E}_B$ does not depend on the mass loss rate.

4) Because the magnetic energy released through the photosphere is much below both the kinetic and thermal energy carried by the wind, the magnetic activity will not heat the region above the photosphere, except perhaps in localized regions where the magnetic energy becomes extremely strong.

5) The solar magnetic activity has a cycle of an 11-year period. If such a cycle exists in upper AGB stars, it will, according to the proposed model, cause oscillations in the mass loss rate. Can it explain the almost periodic shells (or arcs) found in several PNs (e.g., CRL 2688 [Egg Nebula], Sahai *et al.* 1998; IRAS 17150-3224, Kwok, Su, & Hrivnak 1998), and the AGB star IRC+10216 (Mauron & Huggins 1999)?

3. Radiation Shielding by Dust

In a recent paper (Soker 2000) I consider the second type of mechanism, where the increase in the departure from spherical mass loss results from the increase of the mass loss rate. The mass loss rate increases due to the increase of the density scale height (Bedijn 1988; Bowen & Willson 1991). The large quantities of dust formed above a cool spot during the high mass loss rate phase

shields the region above it from the stellar radiation. This leads to both further dust formation in the shaded region, and, due to lower temperature and pressure, the convergence of the stream toward the shaded region, and the formation of a flow having a higher density than its surroundings. This density contrast can be as high as ~ 4. A concentration of magnetic cool spots toward the equator will lead to a density contrast of up to ~ 5 between the equatorial and polar directions. The shielding does not occur for low mass loss rates, hence the positive correlation between mass loss rate and the degree of the departure from sphericity.

An interesting result of the dust shielding is the required spot size. Without shielding, the temperature above a cool spot does not fall with radial distance from the surface as steeply as the temperature of the environment (Frank 1995). For the region to stay cool enough to form dust, the spot must be large: its radius should be $b_s \gtrsim 0.5 R_*$ (Frank 1995). This is a large spot, which is not easy to form by concentration of small magnetic flux tubes (Soker & Clayton 1999). However, with the dust forming very close to the surface, as is suggested for cool magnetic spots (Soker & Clayton 1999), the shielded region forms dust, which in turn shields a region farther away. Therefore, when dust forms very close to the surface of a small cool spot with high optical depth, dust will be formed in the entire shaded region even when the spot is much smaller than what is required without dust shielding. Not only does the proposed flow allow higher mass loss rate from small cool spots, it is also limited to small spots. Above a large spot the relative mass entering from the surroundings is small, and since the radiation from the spot is weaker, the material in the shadow will not be accelerated much.

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